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ELECTRICAL HAZARDS IN INDUSTRIAL FACILITIES AND EVALUATION OF THE MEASURES

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Control measures against electrical hazards in industrial facilities are given in the form of inspection checklists in standards and regulations. In these classic checklists, only the precautions against electric shock are checked within the scope of occupational health and safety. Industrial facilities have not only electrical shock hazards but also arc flash hazards. Therefore, checklists must include precautions against arc flash injuries. To design these measures, the magnitude of the arc flash incident energy must first be calculated. In this paper, the incident energy formula has been evaluated. In addition, new control lines have been added to the inspection checklist for precautions against arc flash hazards. Another important issue is the prioritization of the electrical installation checklist lines by calculating their importance weights. In this prioritization, the analytical hierarchy process, one of the multi-criteria decision-making techniques, was used. 23 experienced inspection engineers were interviewed to create a weighted prioritization table for the 33-line checklist. Thus, occupational safety professionals working in industrial facilities will be able to make an action plan for corrective actions using this prioritization table.

1. INTRODUCTION

Many inspection forms have been created in the literature on testing and inspection of electrical installations. In 1989 J.S. Dudor created an inspection form to quickly catch faults in electrical installations in factories [1]. The paper published by E. J. B. Garnham at the 1988 IEE Conference referred to the importance of electrical installation checks and the priorities of testing required by law in Europe [2]. The paper published by H. Lovegrove at the 1993 IEE conference referred to the importance and harmonized standards of testing and inspections in the UK [3]. The paper published in the IET Wiring Matters Journal in 2011 by P. Bicheno, BS 7671:2008 referred to the innovations in the control forms and the reporting of test and inspection results [4-5]. In the thesis study published by Y. Kisa in 2014 in the General Directorate of Occupational Health and Safety in Turkey, the order of occupational health and safety measures was examined by using Multi-Criteria Decision-Making Methods. The analytical hierarchy process was used to prioritize criteria based on interviews with the occupational physician and HSE specialist [6]. In the paper published by F. Moisiadis at the INCOSE International Symposium in 1999, the methods of prioritizing the requirements were examined [13].

Electrical Internal Facilities Regulation (in Turkey) and TS HD 60364-6:2018 standard explain how to control and inspect the electrical installation. The methods used against electric shock are direct contact protection measures in the context of basic protection measures, indirect contact protection measures in the context of fault protection, and extra-low voltage systems. The most important output expected from the control and inspection of the electrical installation in the context of occupational health and safety is the control of the measures taken against electric shock and the detection of danger points. Corrective actions should begin immediately when dangerous spots are caught.

However, it is not sufficient to check the protection measures against electric shock hazards during the inspection of the electrical installation. There is arc flash hazards and electromagnetic field exposure hazards when operating electrical installations [6,7]. However, in this study, arc flash effects, which are much more dangerous in the context of occupational health and safety, will be discussed.

The paper is organized as follows: The necessity of expanding the classical electrical installation inspection list and the standards examining the arc flash issue are briefly explained in Section 2. In the same section, the incident energy formula in IEEE 1584:2018 is evaluated. Creating layers in the analytical hierarchy process (AHP) to prioritize electrical installation inspection is described in Section 3. In Section 4, the prioritization tables created with the proposed AHP method are presented. Finally, Section 5 summarizes the conclusion.

2. EXPANDING THE CLASSICAL CHECKLIST BY INCLUDING THE CONTROL OF MEASURES AGAINST ARC FLASH EFFECTS

Especially in low voltage electrical installations located in the production halls of industrial facilities, the hazard of injury due to arc flash is very high as well as the hazard of electric shock. Therefore, the scope of inspection should be expanded and not only the precautions against electric shock but also the precautions against arc flash should be checked. To configure the measures against arc flash, the heat energy produced by the arc must be calculated. Thus, the selection of personal protective equipment that can withstand the incident energy is made. To configure the measures against arc flash hazards in the electrical installation, the incident energy calculation is prepared by the design engineer, and the measures are checked by the inspection engineer.

2.1 INCIDENT ENERGY CALCULATION METHODS

The causes of electric arc accidents can be metal dust on live conductors, creatures such as mice gnawing on cable insulation, or metal hand tools that are forgotten while working. In some cases, even equipment with insufficiently tightened terminals can cause arcing. Arc events are more likely to occur in uncontrolled electrical installations. The effects of the arc

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phenomenon on the human body can be summarized as temperature (plasma) effect, pressure effect, shrapnel effect, sound effect, ultraviolet (UV) ray effect, toxin effect, infrared radiation IR effect. To take precautions against the effects of arc energy, the magnitude of this energy and the arc flash boundary must be calculated. The purpose of making incident energy calculations is to determine the risks in terms of the safety of the maneuver and maintenance personnel or the people who will pass by the event and to find the precautions to be taken. The incident energy calculation method in Europe is given in the document DGUV-I 203-077:2020 published by the German statutory accident insurance agency (DGUV). These formulas have also been approved by the International Social Insurance Association (ISSA). In the USA, NFPA 70E:2018 Appendix D summarizes current calculation methods for calculating the arc flash limit and incident energy (Ralph Lee method, Doughty Neal method, and IEEE 1584 method)

2.2 CORRECTION FOR ENERGY FORMULA IN IEEE 1584-2018

Arc energy calculations are given in detail in the "IEEE 1584 Guide for Performing Arc Flash Hazard Calculations". The model uses a two-step process of the intermediate values of the mean arc current, incident energy, and effect distance limit to determine the final values. Coefficients suitable for many different situations in formulas have been developed because of hundreds of experiments.

In this study, the coefficient selection (2.1), and (2.2) were made for the VCB (vertical conductor box) configuration for a 400 V low voltage level. Units and symbols can be rearranged according to the SI international system of units.

$$E_{\leq 600} = \frac{12.552}{50} T.10^{\left\{ \begin{array}{l} k1 + k2 \lg G + \\ \dfrac{k3 I_{arc-600}}{k6 I_{bf}^5 + k7 I_{bf}^4 + k8 I_{bf}^3 + k9 I_{bf}^2 + k10 I_{bf}} + \\ k12 \lg D + k13 \lg I_{arc} + \lg \dfrac{1}{CF} \end{array} \right\}} \quad (2.1)$$

In formula (2.1), in the third term of the exponent, its part other than k3 must be inside the logarithm. Also, the same term should be multiplied not only by k3 but also by sp, whose value is sp = 1.59116.

$$E_{\leq 600} = \frac{12.552}{50} T.10^{\left\{ \begin{array}{l} k1 + k2 \lg G + (k3 \times 1.59116) \times \\ \lg \dfrac{I_{arc-600}}{k6 I_{bf}^5 + k7 I_{bf}^4 + k8 I_{bf}^3 + k9 I_{bf}^2 + k10 I_{bf}} + \\ k12 \lg D + k13 \lg I_{arc} + \lg \dfrac{1}{CF} \end{array} \right\}} \quad (2.2)$$

$E_{\leq 600}$: Incident energy $V_{OC} < 0.6$ kV (J/cm^2)
T: Arc duration (circuit breaker trip time)
G: Gap between conductors
$I_{bf} : I_k^{''}$: 3-phase symmetrical short-circuit current
$I_{arc\text{-}600}$: Arc current (600 V)
D: Distance between electrodes and calorimeters
CF: Enclosure size correction factor
lg G: $\log_{10} G$

A similar correction should be made in the AFB (Arc Fault Boundary) formula.

2.3 PPE (PERSONAL PROTECTIVE EQUIPMENT) SELECTION

Depending on the short-circuit current, according to the result of the incident energy calculation, PPE should be selected in the category in accordance with the NFPA 70E:2018 and IEEE 1584:2018 standards. Cat I-E ≤ 4 cal/cm^2, Cat II-E ≤ 8 cal/cm^2, Cat III-E ≤ 25 cal/cm^2, Cat IV-E ≤ 40 cal/cm^2.

3. CHOOSING A METHOD FOR DETERMINING THE WEIGHT AND PRIORITY OF ELECTRICAL INSTALLATION INSPECTION STEPS

The inspection steps in the electrical installation inspection are not of the same weight and priority. Nonconformities should be prioritized according to their importance and corrective actions should be planned according to this prioritization. For example, the presence of the terminal labeling and the presence of the electrically insulated floor mats in front of the enclosure are not of the same priority. According to the occupational health and safety risk assessment regulations, prioritization must be done according to the magnitude and significance of impacts. Multi-scale decision-making techniques can be used in this prioritization. These techniques offer appropriate methods for prioritizing installation inspection steps. Multi-scale decision-making techniques are included as MCA (Multi-criteria analysis), in the TS EN IEC 31010:2019 standard under the title Risk management -Risk assessment techniques.

Here, the analytical hierarchy process (AHP) method was used as a multi-scale decision-making method. Likewise, the AHP method is the most suitable method that can be used only for prioritizing criteria without alternatives. While determining the criterion weight of the prioritization, it is evaluated using mathematics within the framework of the expert's perception of danger and professional competence [8].

3.1 ANALYTICAL HIERARCHY PROCESS-AHP

The method developed by Thomas L. Saaty in 1977 is a highly effective model in terms of producing statistically and intuitively significant results [9]. Since pairwise comparisons of both discrete and continuous variables are made in the evaluation of AHP, the experience of the decision-making expert becomes important [10].

In the AHP method, after determining the necessary criteria for decision or ranking, the number of variations is reduced by creating appropriate hierarchical layers. After pairwise comparison matrices are created, experts are asked to make pair-wise comparisons. In the comparison, 3, 5 or 9 superiority points are scored. The columns in which the scores are entered are summed up. Each element is divided into the column total and then by taking the averages of the rows, the weights are obtained. It is important that the total weight is 1 (100 %).

The consistency of the found weights must also be evaluated. Likewise, pairwise comparison evaluations should be consistent within themselves. If the CR consistency ratio is not less than 0.1, the evaluation is repeated. The CI consistency index is formed by finding the maximum eigenvalue of the found weights matrix.

3.1.1 CREATION OF HIERARCHY LAYERS IN ELECTRICAL INSTALLATION INSPECTION LIST STEPS EXTENDED BY ARC FLASH

In addition to the control of classical electric shock protection measures specified in TS HD 60364-6: 2016 standard and article 46 of the electrical regulation in Turkey, by considering the measures against the arc flash hazard specified in NFPA 70E:2018 and IEEE 1584: 2018 standards, the following checklist has created the references [1–5].

Terms used in electrical installation inspection:

Check the presence of the measure: It is checked whether a measure is present or not.

The convenience of the measure: The measure is evaluated by comparing it to a specific baseline or by its compliance with the standard. For example, if the continued resistance of the protection conductors R2 < 1 Ω, it is approved.

The first layer of the electrical installation inspection hierarchy is divided into three main control criteria: visual controls, functional tests, and convenience of the measures against the arc flash hazard in the enclosure (Figure 1).

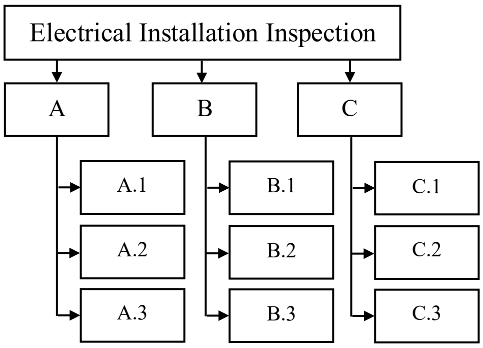

Fig. 1 – Hierarchy of electrical installation inspection, main control criteria.

Visual controls and function tests are defined in TS HD 60364-6:2016 standard and electrical regulation in Turkey at article 46, in the control of classical protection measures against electric shock. In addition, two of the core standards on the effects of arc flash are NFPA70E:2018 and IEEE 1584:2018 standards. The hierarchical creation of the checklist is important in terms of following the method specified in these standards and regulations.

3.1.2 HIERARCHY OF ELECTRICAL INSTALLATION INSPECTION

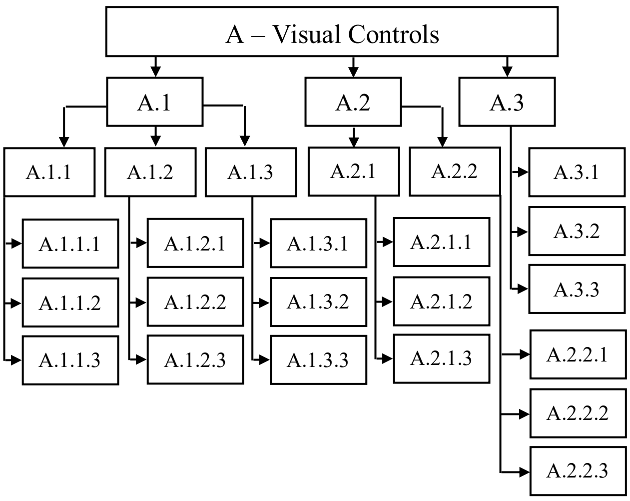

Fig. 2 – Hierarchy of electrical installation inspection, visual control criteria layers.

A) Visual controls (Figure 2).

The visual control is to ensure that the installation complies with safety requirements and does not show any visible evidence of damage.

A.1- Basic protection, protection against direct contact.

A.1.1- Hazards of direct contact with live conductors.

(1) A.1.1.1- Insulation of live conductors

(2) A.1.1.2- Presence of separators before living conductors (IPXXB or IP2X, *etc.*).

(3) A.1.1.3- Presence of electrically insulated floor mats

A.1.2- Convenience of enclosure cover.

(4) A.1.2.1- Presence of enclosure outer cover lock.

(5) A.1.2.2- Presence of enclosure outer cover ert. bridge.

(6) A.1.2.3- Convenience of the enclosure inner cover.

A.1.3-Mechanical convenience of the enclosure.

(7) A.1.3.1- Insulation degree of the enclosure (IPXY)

(8) A.1.3.2- Form type and arc-rated of the enclosure.

(9) A.1.3.3- Seismic (earthquake) convenience of the panel.

A.2- Prevention of mutual detrimental influence.

A.2.1- Proximity to non-electrical metal piping.

(10) A.2.1.1- Proximity of the enclosure to non-electrical pipe installations (metal pipe).

(11) A.2.1.2- Segregation of Band I and Band II circuits or Band II insulation.

(12) A.2.1.3- Segregation of safety circuits.

A.2.2- Identification.

(13) A.2.2.1- Presence of diagrams, instructions, schematics.

(14) A.2.2.2-Presence of danger and warning signs.

(15) A.2.2.3- Labeling of protective devices, and switches.

A.3-Installation cables and conductors

(16) A.3.1- The convenience of cable routes and mechanical protection.

(17) A.3.2- Cable color code. Neutral(N)-Blue, Protection earth (PE)- Green/Yellow

(18) A.3.3- Convenience of cable insulation.

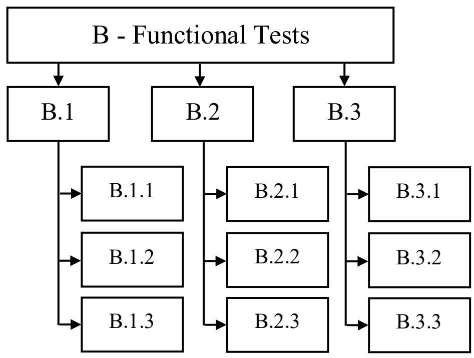

Fig. 3 – Hierarchy of electrical installation inspection, functional test criteria layers.

B) Functional tests (Figure 3).

Functional tests are checks with measuring instruments and monitoring equipment that the installation complies with safety requirements.

B.1- Convenience of the protection device choice.

(19) B.1.1- Convenience between the overcurrent protection Device and relevant cable. $I_b < I_n < I_z$

(I_b = Design Current, I_z = Continuous current rating of cable as provided by cable manufacturers that follows IEC standard, I_n = Nominal current rating of protection devices)

(20) B.1.2- Convenience of RCD.

(21) B.1.3- Convenience of the overvoltage protection device. B.2- Tests performed while the power is off.

(22) B.2.1- Convenience of the continuity test.

(23) B.2.2- Convenience of the insulation test [14].

(24) B.2.3- Convenience of RCD performance tests [12].

B.3- Tests performed while the power is on.

(25) B.3.1- Convenience of earth loop impedance.

(26) B.3.2- Checking the looseness of contact with the

thermal imager.

(27) B.3.3- Checking the cable overload temperature with thermal imager [13].

C) The convenience of the measures against arc flash hazard (Figure 4).

Inspections made at this stage are to check the precautions against arc flash hazard that may occur due to short-circuit current.

C.1- Checking for short circuit effects in the enclosure.

(28) C.1.1- Checking for maximum short circuit current in the enclosure.

(29) C.1.2- Convenience between the short circuit breaking current (Icu) of circuit breaker and the enclosure maximum short circuit current.

C.2- Checking the determination of arc flash's eff. distance.

(30) C.2.1- Checking the distance where the arc flash is most effective.

(31) C.2.2- Checking the distance where arc flash effect is < 1.2 cal/cm^2.

C.3- Checking arc flash effects within working distance.

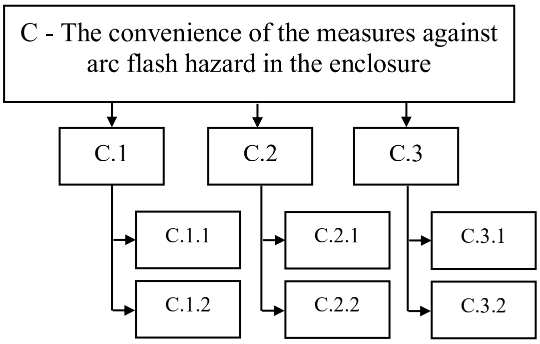

Fig. 4 – Hierarchy of electrical installation inspection, the convenience of the measures against arc flash hazard in the enclosure criteria layers.

(32) C.3.1- Presence of incident energy (cal/cm^2) calculation within working distance.

(33) C.3.2- Presence of arc flash category determination within working distance [15].

3.1.3 EVALUATIONS OF EXPERTS' PAIRWISE COMPARISONS

For the application of the AHP method, 23 expert engineers working in the electrical installation field were consulted. Experts have determined the weight of each step, to prioritize the electrical installation inspection by comparing all control steps in pairs, according to the criteria determined in each step of the hierarchy [16].

Similar rankings can be obtained using fuzzy versions of the AHP based on pairwise comparison matrices. Fuzzy versions appear in many different areas today. Examples are fuzzy logic control in MPPT (Maximum power point tracking) design or fuzzy energy management system in PV (photovoltaic) systems or static var compensator with fuzzy logic control. A similar ranking was obtained by TFAHP (triangle fuzzy analytical hierarchy) [17–23]. Similarly, prioritization was made with the SFAHP (spherical fuzzy analytical hierarchy process) method, and a similar ranking was obtained [24–27].

3.1.4 CHECKING THE RESULTS WITH SUPER DECISION SOFTWARE

Super Decision Software is software designed by Bill Edams and Elena Rokou to solve basic decision problems and was released on 14/01/2019 as version 8.5 to run on Windows operating system. Pairwise comparison matrices of 23 experts were weighted by MS Excel program and all calculations were cross-checked using Super Decision software.

4. **RESULTS**

In this study, multi-scale decision making methods were used to prioritize the developed electrical installation checklist. For this purpose, interviews were held with 23 electrical installation inspection experts on the prioritization of the 33-item inspection checklist. To facilitate the prioritization of the checklist, it is divided into hierarchical layers in accordance with international standards.

Among the 33 inspection items included in the prioritization, circuit breaker suitability and RCD suitability were ranked high in the prioritization by experts. In addition, the control of isolation measures against electric shock hazards that may occur because of direct contact with live conductors has come to the fore in prioritization. Controlling the measures taken to reduce the risk of death and injury from arc flash hazards caused by short-circuit current is among the major priorities of the experts. The nonconformities described in this section are the deficiencies of precautions that have the greatest risk of causing death or injury. Expert evaluations in this context were collected in the first 18 items of the prioritization. Nonconformities in this segment can be termed as "major nonconformities" (Table 1).

Table 1

Major non-conformances

Base	**Electrical Installation Inspection**	W_{AHP}
1-(19)	Convenience between the overcurrent protection device and relevant cable. Ib < In < Iz	8.61 %
2-(1)	Insulation of live conductors	7.54 %
3-(28)	Presence of calculation of the enclosure's maximum short circuit current	6.75 %
4-(18)	Convenience of cable insulation	5.74 %
5-(33)	Presence of arc flash category determination within working distance	4.77 %
6-(2)	Presence of separators before live conductors	4.58 %
7-(20)	Convenience of RCD	4.26 %
8-(32)	Presence of incident energy calculation within working distance	4.06 %
9-(30)	Presence of distance calculation where the arc flash is most effective	3.89 %
10-(3)	Presence of electric insulated floor mats	3.40 %
11-(29)	Convenience between the Icu of circuit breaker and short circuit current	3.35 %
12-(7)	Insulation degree of the enclosure against dust-moisture-water (IPXY)	3.31 %
13-(22)	Convenience of continuity test	3.30 %
14-(21)	Convenience of over voltage protection device	2.90 %
15-(31)	Presence of distance calculation where arc flash effect < 1.2 cal/cm^2	2.66 %
16-(10)	Proximity of the panel to non-electrical metal piping	2.60 %
17-(25)	Convenience of earth loop impedance	2.59 %
18-(26)	Checking looseness of contact with the thermal imager	2.51 %

Major non-conformances:

- Intolerable risk. It must be urgently intervened and corrected, Additional controls are applied.
- Detailed action and planning are required.
- Under the circumstances, work cannot continue.

In the second part, nonconformities with less risk of death or injury are listed (Table 2). Among the 33 inspection items included in the prioritization, cable color code compliance and cable routes compliance ranked low in the prioritization. In addition, inconveniences such as enclosure outer cover earth bridge and enclosure outer cover lock were ranked lower in the prioritization. The lack of precautions described in this section will not directly result in death or injury. These are indirect measures taken to reduce the risk of accidents. Expert evaluations in this context were collected in the rows after the first 18 items of the prioritization. Nonconformities in this segment can be termed "minor nonconformities" (Table 2).

Table 2

Minor non-conformances

Base	Electrical Installation Inspection	W_{AHP}
19-(17)	Cable colour code. Neutral(N)-Blue, Protection earth (PE)- Green/Yellow	2.31 %
20-(16)	Convenience of cable routes in prescribed zones, mechanical protection	2.26 %
21-(24)	Convenience of RCD performance tests	2.22 %
22-(5)	Presence of enclosure outer cover earth-bridge	2.21 %
23-(4)	Presence of enclosure outer cover lock	2.09 %
24-(23)	Convenience of insulation test	2.01 %
25-(8)	Form type and arc rated of the enclosure	1.79 %
26-(27)	Checking the cable overload temperature with thermal imager	1.60 %
27-(12)	Segregation of safety circuits	1.47 %
28-(13)	Presence of diagrams, instructions, schematics	0.99 %
29-(6)	Convenience of the enclosure inner cover	0.92 %
30-(9)	Seismic (earthquake) convenience of the panel	0.92 %
31-(11)	Segregation of Band I and Band II circuits or Band II insulation.	0.91 %
32-(14)	Presence of danger and warning signs	0.74 %
33-(15)	Presence of labelling of protective devices	0.72 %

Expert evaluations in this context were collected in articles 19 to 33 of the prioritization. The nonconformities identified here may be referred to as minor nonconformities.

Minor non-conformances:

- Tolerable risk. Should be fixed as soon as possible.
- It carries low risk. The management employs a special follow-up officer.
- Requires additional controls.

5. CONCLUSION

Ranking the weights of the generalized 33-item inspection checklist in descending order is also ordering the importance weights of the measures to be taken against work accidents. Thus, occupational safety professionals working in industrial facilities will be able to make an action plan for corrective actions using this prioritization table. The prioritization table created in this way can also be divided into other sections depending on the standards and engineering experience. The criteria for determining the section boundaries of the table are related to the severity of the injury that will occur if the precaution is not applied. For example, the danger of contact with live conductors is a major nonconformity, which can lead to death, while the wrong color code of the protective conductor is a minor nonconformity.

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